NASA TECHNICAL TRANSLATION NASA TT F-17128

STUDIES OF RADIOWAVE PROPAGATION IN THE SOLAR SYSTEM

M. A. Kolosov and O. I. Yakovlev

(NASA-TT-F-17128) STUDIES OF RADIOWAVE PROPAGATION IN THE SOLAR SYSTEM (Kanner (Leo) Associates) 33 p HC $4.00 CSCL 20N

N76-28453

Unclas

G3/32 47966

Translation of "Issledovaniye rasprostraneniya radiovoln v solnechnoy sisteme," Rasprostraneniye Radiovoln [Propagation of Radiowaves], Edited by M. A. Kolosov, Moscow, "Nauka" Press, 1975, pp. 291-311

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D.C. 20546 AUGUST 1976

STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No
NASA TT F-17128		

4. Title and Subtitle	5. Report Date
STUDIES OF RADIOWAVE PROPAGATION IN THE SOLAR SYSTEM	August 1976
	6. Performing Organization Code
7. Author(s) M.A. Kolosov & O.I. Yakovlev	8. Performing Organization Report No.
	10. Work Unit No.
9. Performing Organization Name and Address Leo Kanner Associates Redwood City, CA 94063	11. Contract or Grant No. NASw-2790
	13. Type of Report and Period Covered Translation
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration, Washington, D.C. 20546	14. Sponsoring Agency Code

15. Supplementary Notes

Translation of "issledovaniye rasprostraneniya radiovoln v solnechnoy sisteme," Rasprostraneniye Radiovoln [Propagation of Radiowaves], Edited by M. A. Kolosov, Moscow, "Nauka" Press, 1975, pp. 291-311

16. Abstract A review is given of studies of radiowave propagation in the solar system that were conducted from 1963 to 1973 with the Soviet spacecraft Venera, Mars, and Luna. Results are presented for satellite radio occultation investigations of the Martian atmosphere. Properties of radiowave propagation in the dense atmosphere of Venus, involving a radio link with descending spacecraft, are examined along with the basic characteristics of the scattering of satellite-emitted radio waves from the lunar surface. Studies of the propagation of monochromatic radiowaves in the solar plasma are reviewed, and investigations carried out in the United States with the Mariner, Pioneer, and Explorer spacecraft are discussed.

17. Key Words (Selected by Author(s))	18. Distribution Statement
	Unclassified-Unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified		

NASA-HQ

STUDIES OF RADIOWAVE PROPAGATION IN THE SOLAR SYSTEM

M. A. Kolosov and O. I. Yakovlev

Introduction

The first studies of radiowave propagation in the solar system were carried out, in connection with the requirements of radio astronomy and planetary radar. The launches of spacecraft to the planets and the moon stimulated more thorough study of radiowave propagation in the solar system. It became necessary to determine the effect of the environments found on frequency, phase, group time lag, polarization, amplitude and energy spectra of radiowaves in various situations, when the transmitter was located aboard a space vehicle and the receiver on earth. In the solar system, radiowaves can propagate through the atmospheres of planets and through the interplanetary and near-solar plasma; they also can be reflected by the surfaces of the planets or the moon. The basic cases of radiowave propagation in the solar system are shown in Fig. 1. The letters a, b and c designate various cases of the interaction of radiowaves with the environments specified. The dashed curves in Fig. 1 show the trajectories of space vehicles, the arrows mark radiowave beams, and the locations of the vehicles are indicated by the letter T. /291*

In the movement of a space vehicle near the planets or the moon, reflection of the radiowaves emitted by these vehicles from the surface of the celestial body takes place (case a). Since the radiowave source is moving, the Doppler frequency shifts for the direct and reflected waves turn out to be different. On earth, this permits the signals corresponding to the reflected and direct waves to be distinguished and the

* Numbers in the margin indicate pagination in the foreign text.

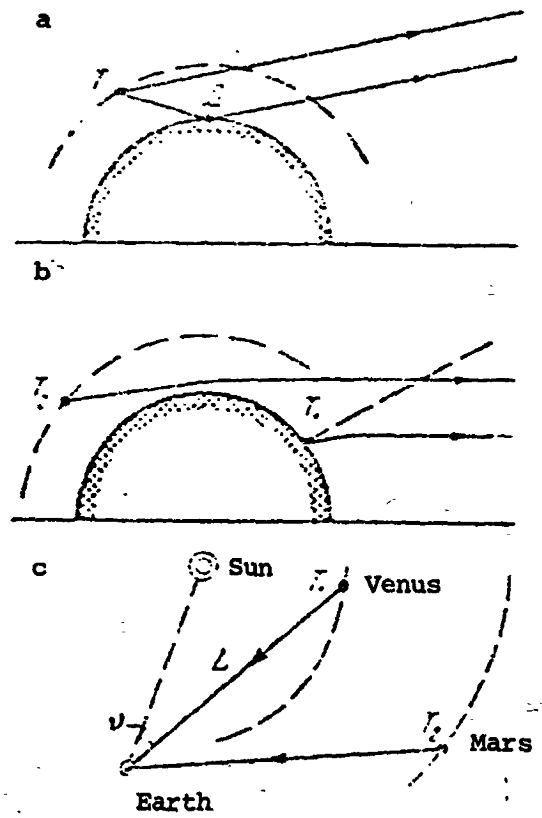

Fig. 1. Basic cases of radiowave propagation in the solar system.

regularities of reflection of the radiowaves in this situation to be studied. In connection with this, the necessity arose for the conduct of analysis of radiowave scattering by a rough sphere, with random locations of the source and receiver. Experimental studies of the reflection of radiowaves emitted from satellites permits determination of the distribution of the dielectric constant, rock density and relief irregularities over the surfaces of the planets or the moon. In principle, it is possible to obtain an image of the surface of a planet by this method.

If a spacecraft is located on the surface of a planet or moves behind the planet, the radiowaves are propagated through the atmosphere of the planet (case b). The regularities of radiowave propagation in the /292 atmospheres of planets depends strongly on the pressure, as a consequence of which the dense atmosphere of Venus has a strong effect and the rarefied atmosphere of Mars has little effect on radiowave propagation. In analysis of radiowave propagation in the atmospheres of planets, 2 cases of location of the space vehicle should be distinguished, when it is on the surface of the planet or moves in the zone of the penumbra behind the planet. With the vehicle located on the surface of the planet, radiowaves, propagating through its atmosphere, can undergo absorption, refraction and fading. If the spacecraft is moving in the penumbra zone and goes behind the planet, radio occultation of the atmosphere occurs. In this case, changes in the radiowave amplitude and frequency are observed. Variations in these quantities recorded on earth give information on the atmosphere and ionosphere of the planet. Radio occultation permits determination of the dependence of pressure, temperature and electron concentration on altitude.

In movement of a space vehicle in a planetary orbit, the radiowaves propagate in the interplanetary or near-solar plasma for distances of several hundreds of millions of kilometers (case c). In this case, the presence of the plasma results in the appearance of phase and amplitude fluctuations, change in the energy spectrum and appreciable time lag of the radiowaves. These phenomena are manifested very slightly in interplanetary space but, in the near-solar plasma under specific conditions, they can be expressed very strongly. Study of the variation of these radiowave parameters enables the interplanetary and near-solar plasma and the conditions of radio communications with interplanetary vehicles to be studied.

The purpose of the work is to survey studies of radiowave propagation in the solar system, performed in 1963-1973, by means of Soviet spacecraft. The results of analogous studies performed in the USA are presented in very compressed form, although the bibliography presented is rather complete.

1. Radio Occultation of the Atmosphere of Mars

The rarefied atmosphere of Mars has a slight effect on radio- /293 wave propagation. This effect is manifested noticeably, only in radio occultation of the atmosphere, in the case of movement of the space vehicle behind the planet. Repeated radio occultation of the atmosphere of Mars was carried out in 1971, by means of the satellite Mars-2 [1, 2]. During movement of the vehicle around the planet, sequential occultations of the ionosphere and troposphere of Mars by decimeter radiowaves (λ = 32 cm) was carried out. In this case, the ground-based deep space communications station received the signals and measured the radiowave parameters. Analysis of the changes of frequency, phase and amplitude of the signals, which occurred in response to the atmosphere of the planet, permitted the regularities of radiowave propagation to be studied and new information on the troposphere and ionosphere of Mars to be obtained.

In radio occultation of the atmosphere of Mars, change in frequency f occurs, both as a consequence of motion of the space vehicle and because of the effect of the atmosphere of the planet. The total frequency change in radio occultation of a spherically symmetrical medium Δf can be described by an expression of the type

$$\Delta f = \Delta f_1 + \Delta F = f v_1 c^{-1} + f v_2 c^{-1} \xi, \qquad (1)$$

where c is the velocity of radiowaves in vacuum; ξ is the angle of refraction in the atmosphere of the planet [3, 4]. The first term of this expression, which depends on projection of the space vehicle velocity vector in the direction of earth v_1, describes the normal Doppler frequency shift. The second term, which is proportional to the projection of the velocity vector perpendicular to the direction to earth v_2, is connected with the parameters of the atmosphere of Mars through angle of refraction ξ. Therefore, the component change in frequency Δf can give information on the atmosphere of the planet studied.

In movement of Mars-2 behind the planet, radio occultation of its ionosphere is carried out first. A typical frequency change ΔF_i in occultation of the ionosphere of Mars is shown in Fig. 2. The value of ΔF_i initially increases approximately exponentially during occultation of the upper part of the ionosphere of the planet, in this case. A sharp decrease in the value of ΔF_i and a change in its sign then occurs, and two characteristic minima then are observed. This frequency change corresponds to occultation of the principal maximum and the lower part of the ionosphere of Mars. With further decrease in altitude of the beam above the surface of the planet, occultation of the troposphere of Mars takes place. A typical curve of change in frequency vs. time for the tropospheric section is presented in Fig. 3.

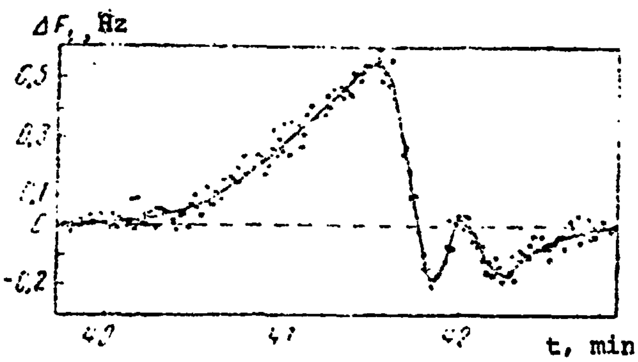

Fig. 2. Change in frequency during radio occultation of ionosphere of Mars.

Since the change in frequency ΔF is proportional to the angle of refraction of the radiowave ξ, the value of ΔF contains information on the angle of refraction of radiowaves in the atmosphere of Mars. Experimental curves of the angle of refraction of radiowaves vs. beam altitude in the ionosphere and troposphere of Mars are presented in Figs. 4 and 5. The numbers near the curves in Figs. 4 and 5 correspond to the numbers of the experiments in radio occultation of the atmosphere of the planet. The positive values of angles $\xi_{t.i}$ in these figures correspond to deflection of the radiowave beam to the outside, with respect to the planet, and negative values indicate deflection of the beam toward the planet. The angle of refraction in the troposphere ξ_t depends on the pressure. Because /294

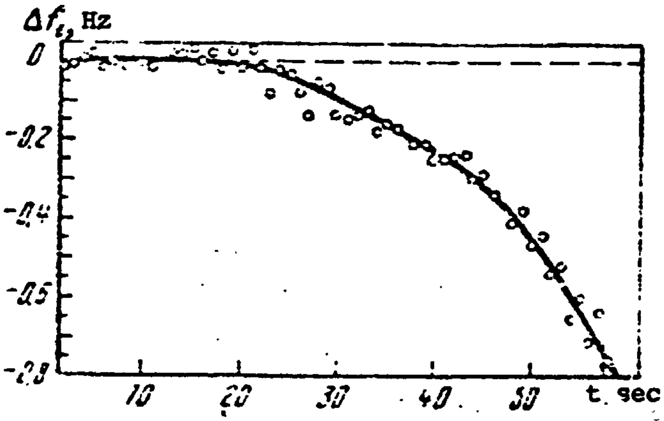

Fig. 3. Change in frequency during radio occultation of troposhpere of Mars.

of the effect of the relief, the zero altitudes did not coincide in different experiments.

During movement of the vehicle behind the planet, a diffraction change in field intensity is observed. An example of radiowave diffraction on Mars is presented in Fig. 6. A theoretical analysis of radiowave diffraction on a planet having a highly rarefied atmosphere

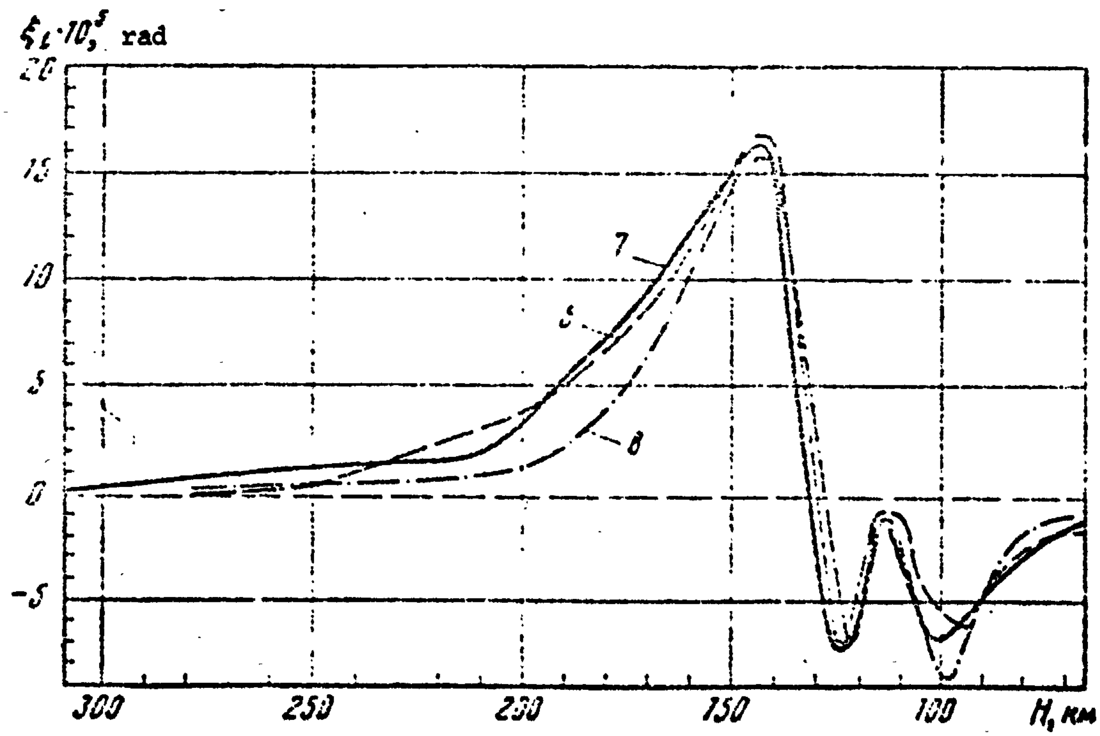

Fig. 4. Angle of refraction of radiowaves in ionosphere of Mars vs. altitude above surface of planet. Numbers on curves, experiment number.

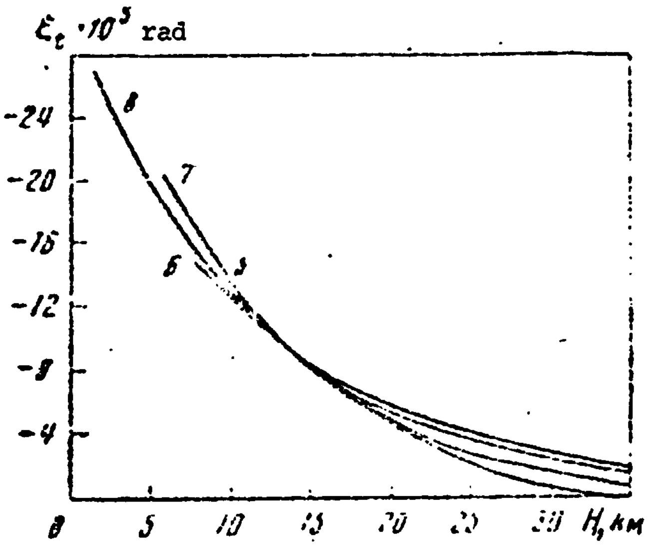

Fig. 5. Angle of refraction of radiowaves in troposphere of Mars vs. altitude of beam above surface of planet. Numbers on curves, experiment number.

was given in works [5, 6]; it was shown here that a small refraction attenuation of the radiowaves is superimposed additionally on the diffraction change in field strength, and that the diffraction curve is shifted by a small angle of refraction ξ. The refraction attenuation depends on the distance between the spacecraft and the edge of the disc of the planet; in the experiments described, this attenuation was negligibly small. The time of contact of the beam on the surface of the planet is found

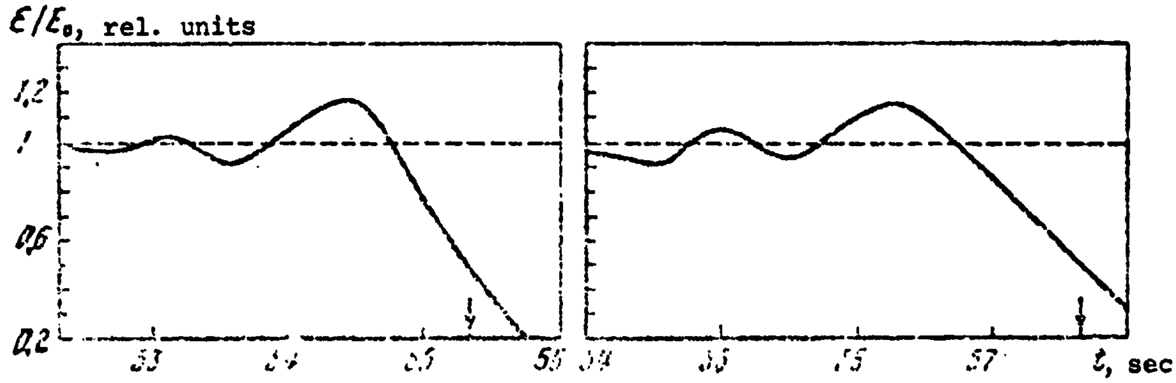

Fig. 6. Diffraction change in field intensity during movement of Mars-2 behind planet.

from the diffraction curves of the change in field intensity. This time is defined as the moment of decrease of the field intensity by half; this moment is indicated by the arrow in Figs. 3 and 6. Knowledge of velocity component v_2 and this moment of time permits the altitute of the beam above the surface of the /296 planet H to be found and, consequenctly, the measurements of the angles of refraction and parameters of the atmosphere to be tied in to specific altitudes.

The experimental functions ξ (H) found permitted new information to be obtained on the daytime atmosphere in the equatorial regions of Mars. The angle of refraction is connected by the known relationship $n(h) = 1 + N(h)$, to the dependence of the coefficient of refraction of the radiowaves on altitude. By application of an Abel transform to the refraction integral, the corrected coefficient of refraction $N(h)$ can be found [7]. In the case of a slightly refracting, spherically symmetrical medium, this relation has the form

$$N(h) = \frac{1}{\pi} \int_h^\infty \frac{\xi(H)\, dH}{\sqrt{(a+H)^2 - (a+h)^2}}, \qquad (2)$$

where H is the minimum altitude of the beam above the surface of the planet; h is the altitude of an arbitrary point in the atmosphere of Mars; a is the radius of the planet. Relationship (2) allows determination of the density of atoms in the troposphere and the electron concentration in the ionosphere of Mars, since the corrected coefficient of refraction of radiowaves is proportional to these values. It is significant that the radio occultation method also permits determination of the temperature and pressure in the troposphere of the planet.

The experiments showed that the concentration of atoms at the surface of the planet in various regions was $1.7\text{-}3.3 \cdot 10^{17}$ cm^{-3}, and the corresponding pressures were 5-10 mb. Pressure vs. altitude curves, found from the data of several experiments, are presented in Fig. 7. Since the surface pressure depends on the relief of the planet, function $p(h)$ is displaced to the point where the pressure equals 5 mb, and a provisional zero altitude of the surface is introduced. It follows from Fig. 7 that, in the areas of the planet studied, the average altitudes were ±4 km, and the pressure a' the provisional zero altitude is 7 mb.

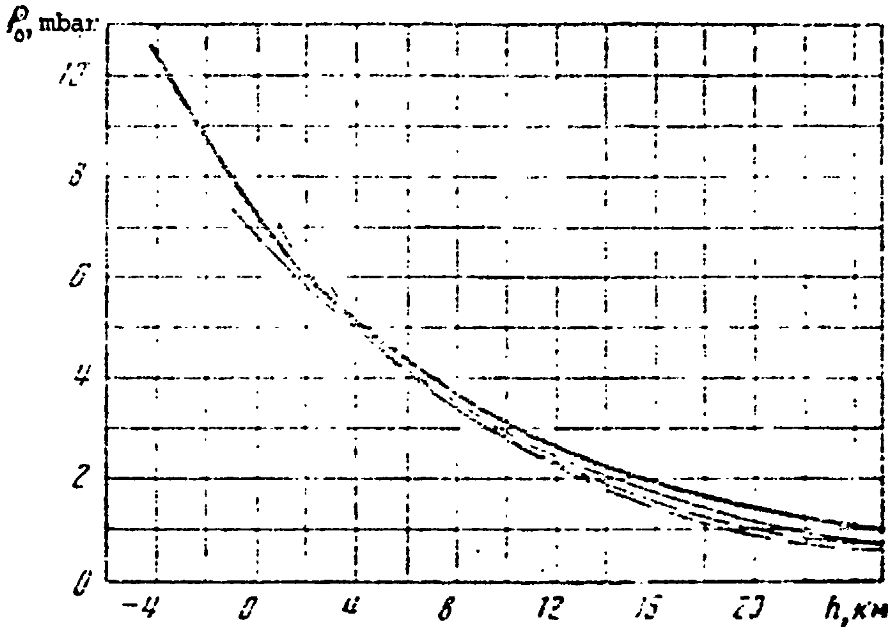

Fig. 7. Pressure vs. altitude in troposphere of Mars.

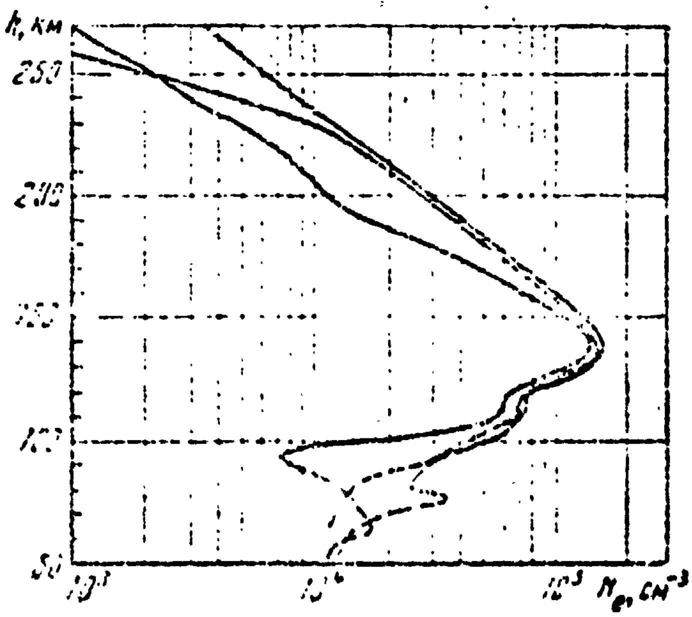

Fig. 8. Electron concentration vs. altitude in ionosphere of Mars.

Three altitude profiles of electron concentration in the ionosphere of the planet, determined by radio trans-illumination by means of Mars-2 are presented in Fig. 8. In the altitude section h=150-250 km, the electron concentration increases approximately exponentially, and the altitude scale for this interval is 35 km. At an altitude of 200 km, the electron concentration was $3.4 \cdot 10^4$ cm^{-3}. The principal

maximum of the electron concentration, with a value $Ne=1.7 \cdot 10^5$ cm^{-3}, was recorded at an altitude of about 140 km. With further decrease in altitude, the electron concentration begins to decrease, but a second maximum is found at an altitude of 110 km, with an electron concentration of $7.5 \cdot 10^4$ cm^{-3}. At altitudes of /297
less than 95 km, the electron concentration decreases, but a third ionospheric maximum is observed approximately at an altitude of 70 km, with an electron concentration on the order of 10^4 cm^{-3}. Compared with the terrestrial ionosphere, the Martian ionosphere is less extended and more held down to the surface of the planet.

Radio occultation of the atmosphere of Mars also has been carried out in the USA, by means of the Mariner spacecraft [8-11]. The data obtained by means of these vehicles on the troposphere and ionosphere of the planet correspond well to the /298
results of the Soviet studies. It is significant that the wavelengths and trajectories of the vehicles were different. This indicates the reliability of the radio occultation method for study of the atmospheres of planets. At present, there are detailed experimental data on the effect of the troposphere and ionosphere of Mars on the radiowave parameters, during passage of the spacecraft behind the planet.

2. Studies of Radiowave Propagation in the Atmosphere of Venus

In studies of Venus by means of Soviet descent vehicles, study of radiowave propagation in the dense atmosphere of this planet was carried out. Venera-4 was the first to reach the planet, and it emitted radio signals through the atmosphere of Venus. This fact gave an impetus to study of radiowave propagation in the case of location of the space vehicle in the atmosphere or on the surface of Venus. Preliminary results of analysis of this task were presented in works [12-14]. Subsequent studies, carried out by means of the Venera-5, 6, 7 and 8 vehicles, gave specific information on the atmosphere of the planet and permitted the basic regularities of radiowave propagation in the atmosphere of Venus to be found [15-18].

Radiowave attenuation in the atmosphere of Venus can be caused both by absorption and by refraction effects. Radiowave absorption in carbon dioxide, with admixture of other components, has been studied under laboratory conditions [19]. However, this study was carried out, by means of determination of the small change in Q factor of a resonator filled with gas. Transfer of these results to the dense and extensive atmosphere of Venus may result in inaccuracies which do not yield to evaluation. In connection with this, the accomplishment of direct tests of radiowave propagation in the atmosphere of this planet is important.

Study of radiowave propagation in the atmosphere of Venus, by means of the Venera-7 and 8 descent vehicles was carried out in the following manner. After entry of the vehicles into the atmosphere of Venus, opening of the parachutes and turning on of the transmitters, over a period of 13-16 min radio signals were received from the upper part of the atmosphere, where the pressure was less than 20 atm. It was known beforehand that this part of the atmosphere should not affect attenuation of decimeter radiowaves. A relatively fast descent of the vehicles to the surface of the planet then took place. The descent in the h=20-0 km altitude section, where the pressure changed from 25 atm to 90 atm, took 17 and 33 min, respectively, for Venera-7 and Venera-8. In this time, the transmitter power was practically constant. It is significant that, after the descent, the vehicles emitted radiowaves from the surface of the planet for a long time. During measurements of the signals of Venera-7, the radiowaves propagated along the vertical in the atmosphere of the planet but, in the case of Venera-8, the zenith angle of the radio beam on Venus was 40°. Measurements of the energy flux of the radiowaves, with the vehicles located at various altitudes above the surface of Venus, are presented in Fig. 9. It follows from Fig. 9 that, in propagation of radiowaves of the λ=32 cm range through the entire atmosphere of Venus, with a zenith angle of beam on Venus of less than 40°, attenuation of the radiowaves is not observed. /299

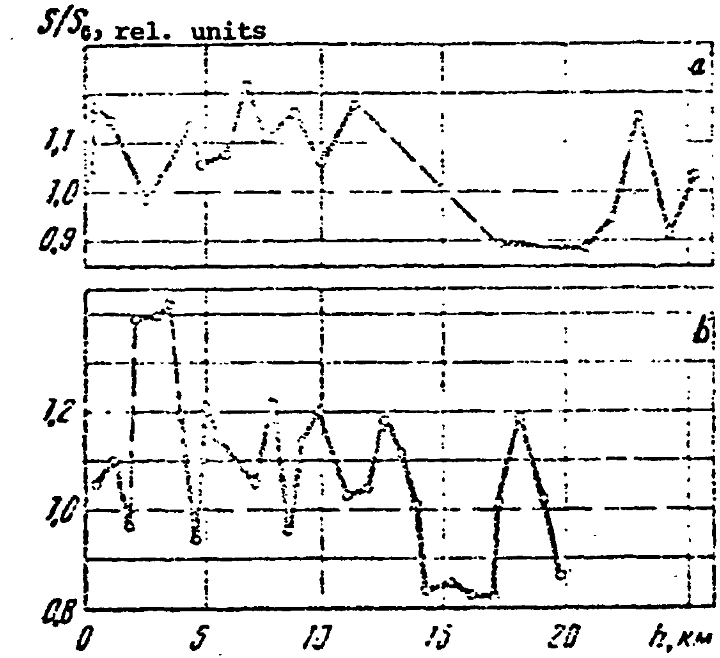

Fig. 9. Constancy of average energy flux of radiowaves during descent of Venera-7 (a) and Venera-8 (b) to surface of planet.

In the centimeter wave range or at larger zenith angles of the beam, the atmosphere of Venus should attenuate radiowaves. The decrease in radiowave energy S in the atmosphere of this planet, in the general case, is caused by absorption and refraction attenuation of radiowaves. It is expressed by an approximate formula of the type

$$S = S_0\left(1+\left|\frac{d\xi}{d\beta}\right|\right)^{-1}\exp\left(-\tau\lambda^{-2}\sin^{-1}\beta\right), \qquad (3)$$

where ξ is the angle of refraction; β is the angle of site of the beam; τ is a parameter. The first factor in (3) describes refraction attenuation of radiowaves, caused by expansion of the beam tube. It depends on the derivative of the angle of refraction over the angle of site of the beam $d\xi/d\beta$. The second factor takes absorption of radiowaves into account; it depends on wavelength λ and parameter τ=12 cm^{-2}. The results of calculations of the dependence of total attenuation of the radiowave energy flux on wavelength, for three angles of site, are presented in Fig. 10. Curves 1, 2 and 3 are given for angles of site of the beam of 90°, 30° and 12°, respectively, in the case of location of the transmitter on the surface of Venus. Radiowave absorption in the /300
atmosphere of this planet has been studied by radar ranging [20, 21]. The results of calculations of the radiowave attenuation presented in Fig. 10 correspond to direct experiments, carried out by means of descent vehicles, information on the gas composition and pressure in the atmosphere of Venus and radar data.

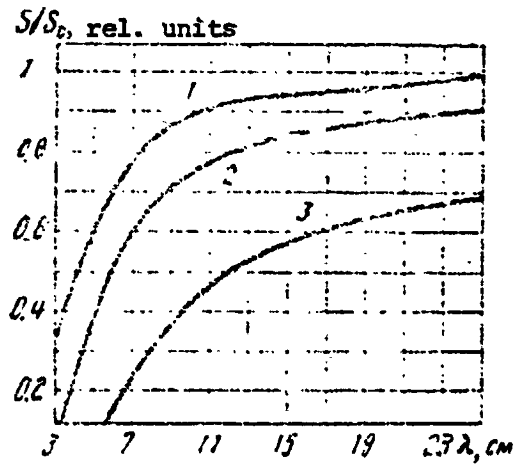

Fig. 10. Radiowave energy attenuation in atmosphere of Venus vs. wavelength. 1. 90°; 2. 30°; 3. 12°.

Irregularities in the coefficient of refraction of the atmosphere of Venus are due to the appearance of mild fading of the radiowaves. An experimental curve of the extent of rapid fluctuations of field intensity of the λ=32 cm radiowave range vs. altitude of the vehicle above the surface of the planet, with vertical propagation of the radiowaves, is shown in Fig. 11. Data obtained by means of Venera-5 and Venera-6 (1), the results of

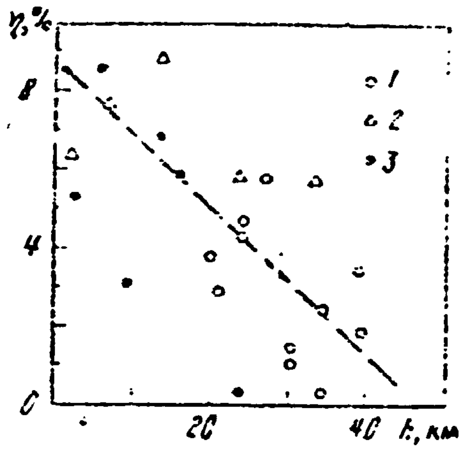

Fig. 11. Degree of fluctuation of decimeter radiowave field intensity vs. altitude of vehicle above surface of Venus. 1. Venera-5 and Venera-6 data; 2. Venera-7; 3. Venera-8 data.

processing of the signals of Venera-7 (2) and radiowave fluctuations according to the data of Venera-8 (3), are presented in Fig. 11. These fluctuations have a characteristic period of about 3 sec. Slow variations in field intensity also were observed during radio communications with the descent vehicles. These variations could have been due to both swinging of the descent vehicle and the effect of large scale irregularities of the atmosphere of the planet. In connection with this, the only recording of the Venera-8 signals received after its landing on the surface of the planet were used to estimate the slow variations. Analysis showed that, after landing, slow variations in field intensity, to the extent of about 10%, were observed.

The irregularities in the coefficient of refraction of the atmosphere of Venus can be due to both large scale meteorlogical /301 formations and turbulence of its atmosphere. If it is assumed that the rapid fluctuations of the radiowaves were caused by atmospheric turbulence, the extent of fluctuation of the field intensity is determined by an approximate expression of the type

$$\Delta = 0.43\lambda^{-7/12}(\sin\beta)^{-11/12}. \quad (4)$$

This formula results from the known theory of fluctuations in a turbulent atmosphere and the experimental data described [17, 18]. It holds true for an angle of site of the beam β greater than 10°. A more detailed analysis of the radiowave fluctuations in the atmosphere of Venus was carried out in [15-18, 22].

Refraction of radiowaves in the atmosphere of Venus was expressed very strongly. The corrected coefficient of refraction of radiowaves in the atmosphere of Venus depends on altitude in the following manner:

$$N(h) = \exp(-ah^2 - bh - c), \qquad (5)$$

here, a, b and c are numerical parameters [52]. The angle of refraction in the case being considered is determined by a certain integral, in which the specified function N(h) should be incorporated. At a beam angle of site β=20°, the angle of refraction turns out to be 2.6°. If the angle of site β approximates 9°, the beam line is deflected so much that it does not go beyond the atmosphere of Venus. In connection with this, radiowave attenuation and fluctuations cannot be predicted sufficiently reliably for small beam angles of site.

During movement of a space vehicle near Venus, it is possible to carry out radio occultation of its atmosphere. Since Venus has a dense atmosphere, in radio occultation, a strong change in radiowave amplitude and frequency should be observed. In 1967, in the USA, a single radio occultation of the atmosphere of Venus was carried out, by means of Mariner-5 [23, 24]. The authors of these works used the recorded changes of radiowave amplitude and frequency to obtain dependences of the electron concentration in the ionosphere, and pressure and temperature in the troposphere of the planet on altitude. It is significant that, in radio transillumination of the atmosphere of Venus, the beam does not penetrate deeper than the critical refraction level, which is located at an altitude of 34 km. In works [4, 25, 26], additional possibilities of study of the atmosphere of Venus by radio transillumination are considered. It is highly effective for study of the upper part of the atmosphere and ionosphere of Venus.

3. Study of Reflection of Radiowaves Emitted by Satellites from the Surface of the Moon and Planets

If a source of radiowaves moves near the planets or the moon, the radiowaves are reflected by the surfaces of these celestial bodies. This permits study of the reflection of radiowaves by various sections of the surface of the planet or moon. It is important that the region essential for reflection of radiowaves in the direction of the earth be small, in this case; during movement of the satellite of a planet or the moon, it "traverses" the surface of the celestial body. This permits the reflective properties of various sections of the celestial body to be studied. The value of the coefficient of reflection and the shape of the energy spectrum of scattered radiowaves give information on the dielectric constant, rock density and degree of roughness of the relief of the section of the surface studied. This problem was studied in detail in the USSR, in works [27-34]. Similar studies in the USA are described in [35-39]. /302

The problem under consideration and its theoretical formulation are reduced to analysis of the scattering of waves by a rough sphere, with arbitrary location of the moving radiowave source. Known regularities of radiowave scattering by an area of limited roughness, but flat on the average, are used in solution of this problem. If the surface of the planet or moon is represented in the form of a set of such areas, tangent to the spherical surface, the density of the energy flux of scattered radiowaves can be determined by integration of the energy fluxes from each elementary area. The power coefficient of reflection of the radiowaves η^2 in this problem equals the ratio of the density of the scattered radiowave energy flux S to the density of the energy flux S_0, which would be observed on the earth, if the planet were replaced by an ideally conducting plane, tangent to the sphere at the point of mirror reflection of the radiowaves. Introduction of such a definition is due to the fact that the value of η turns out to be equal to the ratio of the field intensities of the scattered and direct waves, with a nondirectional satellite antenna. It was shown in work [28] that the power coefficient of reflection, for the case of emission of radiowaves from the satellite and their reception on earth, can be represented by an approximate expression of the type

$$\eta^2 = \frac{sM^2(\pi a^2)}{4\pi R^2}, \qquad (6)$$

where M is the Fresnel coefficient of reflection; a is the radius of the planet or moon; R is the distance from the satellite to the provisional point of mirror reflection of the radiowaves. The value of s is determined by the following relationship:

$$s = \frac{1}{2\pi a^2\gamma^2 q_{z1}^2}\int \exp\left(-\frac{q_x^2+q_y^2}{2\gamma^2 q_z^2}\right) ds, \qquad (7)$$

where γ is the mean slope of the surface irregularity; $q_{x,y,z}$ are the projections of the scattering vector. The integration in (7) is carried out over the portion of the surface of the planet, which is simultaneously visible from the satellite and from the earth. Expression (6) has a simple physical meaning. Quantity $(4\pi R^2)^{-1}$ characterizes the decrease in density of the radiowave energy flux incident on the scattering surface with increase in /303
distance R. Factor s shows how much the scattering surface is smaller than the cross section area of the planet; this factor

takes account of the sphericity and roughness of the scattering surface. The effect of the dielectric constant in (6) is reflected by Fresnel coefficient M. As an example, the results of calculation of the intensity coefficient of reflection vs. the grazing angle of the radiowaves for a satellite of the moon is presented in Fig. 12. Curve 1 corresponds to a satellite altitude of 100 km, and curve 2 is given for an altitude of 800 km. It was assumed in the calculations that $\varepsilon=3$ and $\gamma=0.15$. A comparison of these data with the case of reflection of radiowaves by a smooth sphere shows that, at grazing angles $\phi>50°$, the coefficient of reflection of a rough and a smooth sphere practically coincide. At angles $5°<\psi<30°$, a rough sphere has a somewhat larger coefficient of reflection than a smooth sphere of the same dielectric constant of the material.

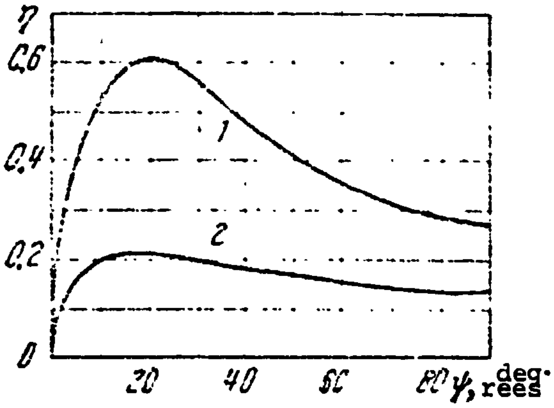

Fig. 12. Intensity coefficient of reflection vs. radiowave grazing angle ψ for satellite of the moon. 1. 100 km; 2. 800 km.

Experimental studies of the coefficients of reflection of radiowaves were carried out, by means of the satellites Luna-11, Luna-12 and Luna-14, in the meter wave range [28, 29, 33]. The intensity scattering coefficient η vs. radiowave grazing angle ψ, for a satellite altitude of 250 km, obtained by means of the satellite Luna-14, in the $\lambda=1.7$ m range, is presented in Fig. 13. The theoretical curve (dashed) corresponds to a dielectric constant $\varepsilon=2.8$ and a mean slope of surface irregularity $\gamma=0.15$. Since parameter γ has little effect on the coefficient of reflection, the dielectric constant is easily determined from the values of the coefficient of reflection measured in this manner. By means of the satellite Explorer-35, the coefficient of reflection with /304

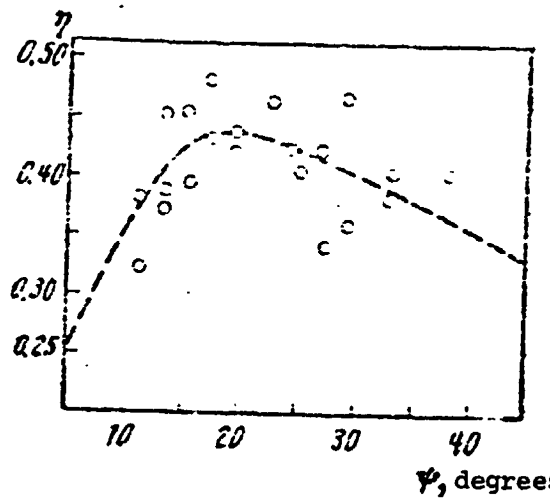

Fig. 13. Experimental values of coefficient of reflection of meter waves from the lunar surface, from data of Luna-14 satellite.

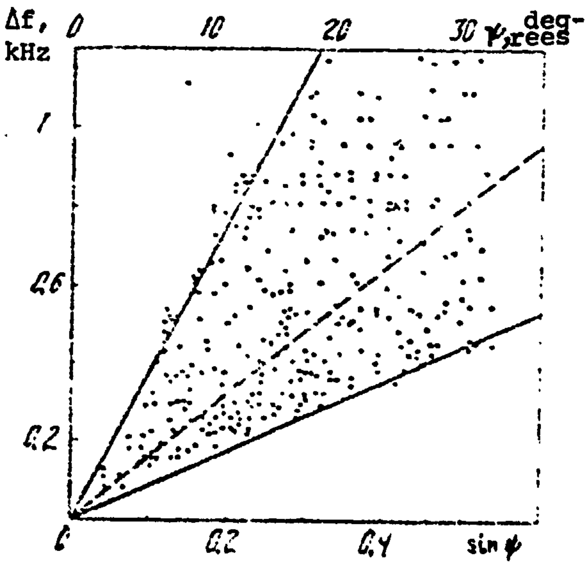

Fig. 14. Spectral width of scattered radiowaves at various grazing angles ψ, from satellite Luna-19 data.

vertical radiowave polarization was successfully measured and the Brewster angle was determined [36]. According to the data of this work, the grazing angle, at which the Brewster minimum of the coefficient of reflection was recorded, is 30°, which corresponds to ε=3.

Radiowaves scattered by various sections of a planet or the moon have various Doppler frequency shifts. This results in formation of a diffuse energy spectrum of the scattered radiowaves. The energy spectra of scattered radiowaves, in the case of their emission from a satellite of the moon and reception on the earth, were analyzed in works [29, 30, 32-34]. The analysis showed that the width of the energy spectrum depends strongly on the grazing angle of the radiowaves and the degree of roughness of the scattering surface. This conclusion of the theory was confirmed experimentally. It turned out that the width and shape of the energy spectrum are sensitive to the nature of the relief of a small section of the surface, corresponding to the radiowave mirror reflection point. The dependence of spectral width on grazing angle is manifested only after averaging much experimental material. Spectral widths by half-power level vs. radiowave grazing angle, for $\lambda=32$ cm, is presented in Fig. 14. A comparison of the experimental and theoretical spectra permits determination of the provisional mean slope of the surface roughness γ. The studies showed that the roughness of the Sea of Serenity is characterized by $\gamma \approx 2°$ and, for the very rough sections including Schickard, Humboldt and Vendelinus craters, $\gamma \approx 6-9°$ was obtained.

The problem of the scattering of radiowaves emitted by satellites by the surfaces of planets or the moon has now been studied in sufficient detail. The theory developed in the approximation of Kirchoff corresponds well with the experimental data. The radio reflection method has proved to be effective for study of the distribution of dielectric constants, density and characteristic relief forms over the surface of a celestial body.

This method, in principle, permits construction of a visible image of the surface of a planet with high resolution, according to the radio holography principle [52]. In order to obtain a visible image of the surface relief by means of reflected radiowaves, an unequivocal correspondence between the coordinate of an arbitrary point on the surface of the planet and the "radio /305
brightness" of a small area including this point must be found. This task is reduced to a search for the principle of processing reflected radiowaves received on the earth, which permits a connection of the coordinates of the point and the "radio brightness" of the corresponding section of the surface to be found. This is similar to the methods used in side-viewing radar.

4. Monochromatic Radiowave Propagation in Near-Solar Space

In movement of a spacecraft in the solar system, radiowaves propagate in a rarefied, heterogeneous, rapidly moving plasma. In this case, phase and amplitude fluctuations, a change in the energy spectrum and a time lag of the radiowaves are manifested. Since the electron concentration decreases with increase in distance r from the sun, approximately according to $N_e \simeq r^{-2}$, it has a stronger effect near the sun. The results of study of propagation of monochromatic radiowaves in the interplanetary and near-solar plasma have been presented in works [40-48].

A theoretical analysis of the phase and amplitude fluctuations and the changes in the radiowave energy spectrum was carried out in works [43, 45]. In these articles, the known theory of fluctuation of waves in a statistically heterogeneous medium was used, with a Gaussian autocorrelation function of fluctuations of electron concentration. In this case, it is taken into account that the heterogeneity of the electron concentration decreases with increase in distance from the sun, according to $\Delta N_e \simeq r^{-2}$. The analysis showed that the root mean square of the phase fluctuations is determined by an expression of the type

$$\langle\Delta\Phi^2\rangle = \frac{A\varkappa^2 l}{f^2}\int_0^b \frac{\left[2+q^2\left(\frac{b-x}{b}\right)^2 x^2\right]dx}{\left[1+q^2\left(\frac{b-x}{b}\right)^2 x^2\right]\left[x^2-2x\cos\nu+1\right]}. \qquad (8)$$

Here, ℓ is the scale of heterogeneity of the electron concentration, expressed in km; f is the frequency in MHz; parameter $\kappa = 0.3\cdot 10^{26}$ cm^{-1}, $A=2\cdot 10^{-44}$ cm$\cdot$sec^{-2}; b=L/a is the ratio of the path length to the astronomical unit; $q=2a\lambda/\pi\ell$, $a=1.5\cdot 10^{8}$ km. The root mean square fluctuation of field intensity is expressed by the relationship

$$\left\langle\left(\ln\frac{E}{E_e}\right)^2\right\rangle = \frac{A\varkappa^2 l q^2}{f^2}\int_0^b \frac{\left(\frac{b-x}{b}\right)^2 x^2 dx}{\left[1+q^2\left(\frac{b-x}{b}\right)^2 x^2\right]\left[x^2-2x\cos\nu+1\right]}. \qquad (9)$$

The heterogeneities of the electron concentration in expressions /306
(8) and (9) are described by parameters κ and ℓ, and the radio communications path is fixed by its length L=ba and angle ν. Angle ν characterizes the location of the beam relative to the sun; this is the angle between the direction to the center of the sun and to the spacecraft, with the apex on the earth (Fig. 1c).

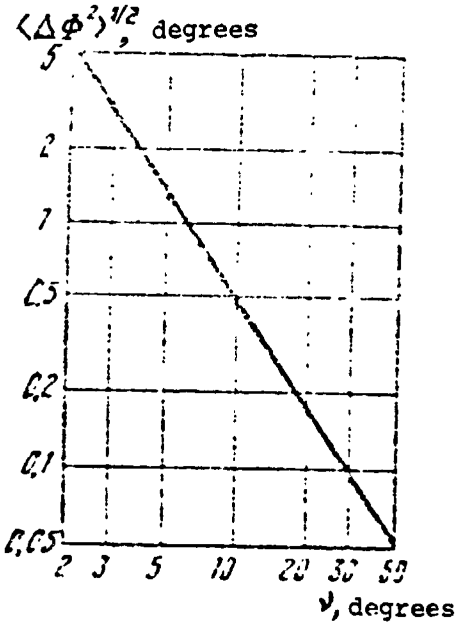

Fig. 15. Phase fluctuations vs. angle ν.

The calculated radiowave phase and amplitude fluctuations vs. angle ν, for a path 300 million km long and frequency f= 1000 MHz, are presented in Figs. 15 and 16. The radiowave fluctuations depend slightly on path length L. Therefore, these graphs hold true at L=200-400 million km. The phase fluctuations in the problem under consideration are inversely proportional to frequency, and the amplitude fluctuations for f>500 MHz are inversely proportional to the square of the frequency. Experimental studies of radiowave amplitude fluctuations were carried out by radio astronomy methods [50]. These studies correspond to the case of location of the radiowave source at infinity. Recalculation of the radio astronomy data was carried out in work [45], for the case of radio communications with interplanetary stations, and good correspondence of the theory of amplitude fluctuations and the experimental data was demonstrated. Motion of the heterogeneities of the near-solar plasma should result in spreading of the radiowave energy spectrum. The theory of this phenomenon was presented in [41-43, 45], and the corresponding experimental

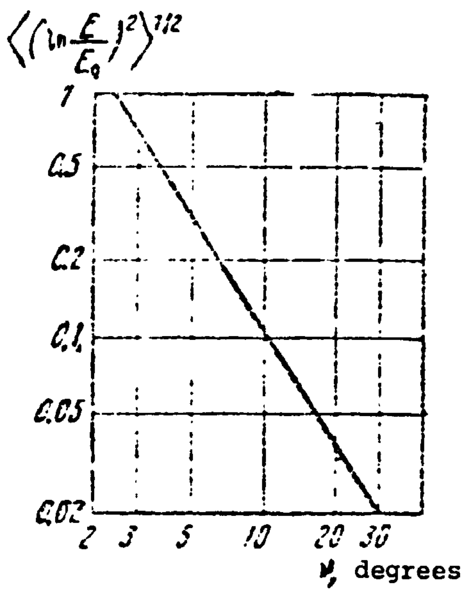

Fig. 16. Fluctuations of log field intensity vs. angle ν.

data were presented in works [46, 47]. The spreading of the radiowave spectrum was due basically to phase fluctuations. It appears rather distinctly at $\nu<10°$.

Detailed studies of radiowave propagation through the near-solar plasma were carried out, by means of the spacecraft Mars-2. Angle ν was changed /307
from 30° to 2° in this experiment, and the path length was about 400 million km. Increasing variations in frequency, phase and amplitude and spreading of the radiowave spectrum were recorded with decrease in angle ν. The energy spectra of the radiowaves emitted by the spacecraft /308
Mars-2 are presented in Fig. 17, for various angles ν. It was shown in works [44, 45] that, with large phase fluctuations, the width of the radiowave energy spectrum by half-power level is proportional to the velocity of the near-solar plasma V and inversely proportional to the scale of heterogeneity ℓ:

$$\Delta F = V\langle\Delta\phi^2\rangle^{1/2}/\sqrt{\pi}\,l. \qquad (10)$$

Here, $\langle\Delta\phi^2\rangle^{1/2}$ is the mean phase fluctuation, determined by expression (8). Expression (10) holds true at $\nu<10°$.

The near-solar plasma causes a noticeable time lag in radio- /309
waves. Measurement of the radiowave time lag at 2 frequencies permits the distribution of electron concentration near the sun

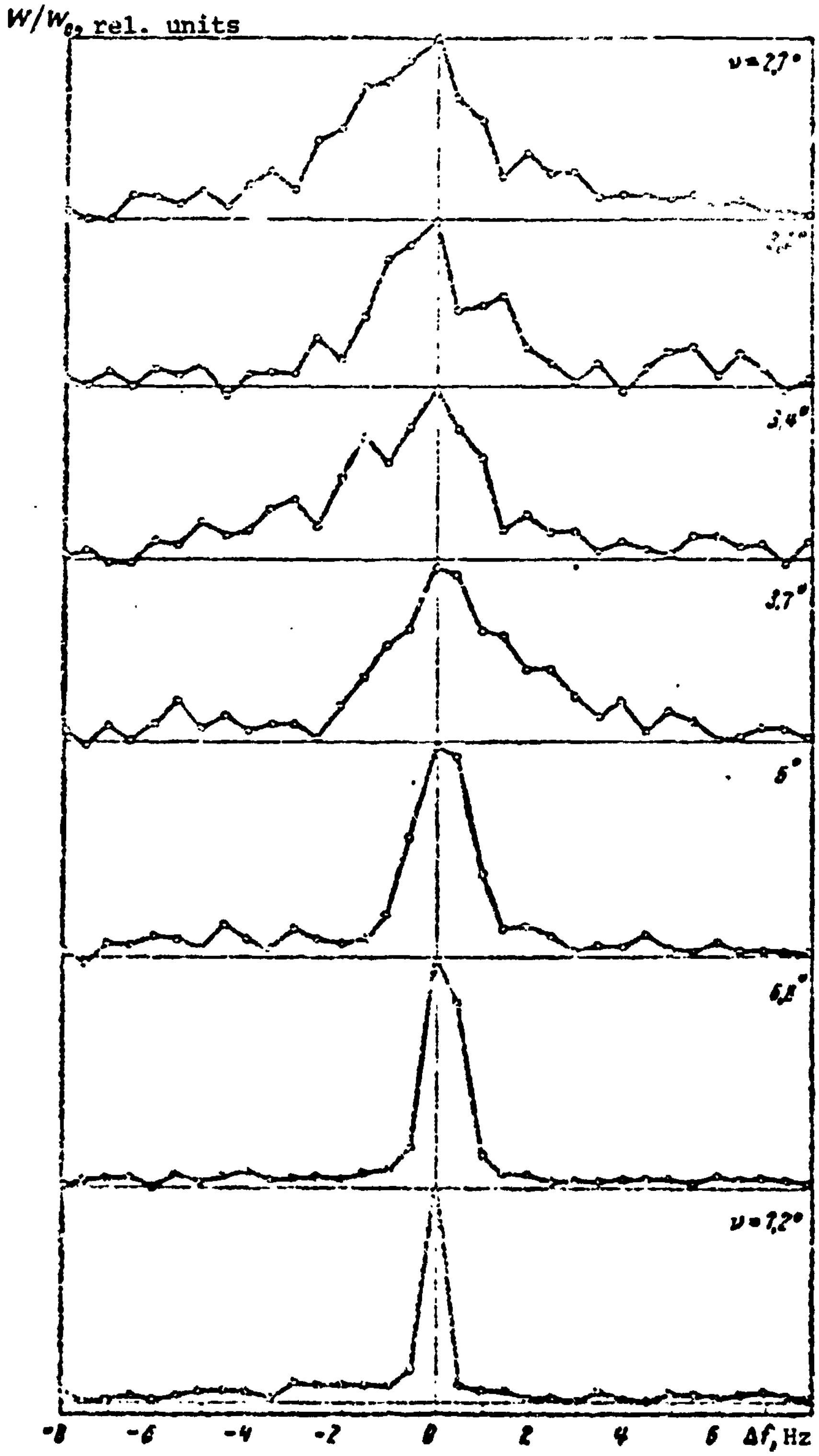

Fig. 17. Radiowave spectrum spreading in near-solar plasma.

to be studied [51]. There also is great interest in investigation of the radiowave time lag caused by the gravitational field of the sun. This phenomenon was investigated in work [49].

The magnetic field of the sun should cause a rotation of the plane of polarization of radiowaves. This effect was studied in work [48], where the distribution of electron concentration in the near-solar plasma was successfully measured, with the use of the Faraday effect.

5. Radio Astronomy with Artificial Sources

At the present time, the basic regularities of radiowave propagation in the solar system have been rather well studied. The results of these studies, described in the survey, have enabled new methods of study of the surfaces and atmospheres of the planets and the moon and of the interplanetary and near-solar plasma to be developed. Study of objects in the solar system by radiowave propagation methods has resulted in the development of a new section of radio astronomy studies, radio astronomy with artificial sources. The basic studies carried out by radiowave propagation methods, by means of spacecraft, are indicated in Table 1. This table illustrates the possibilities of radio astronomy with artificial sources.

The basic regularities of radiowave propagation in the solar system were briefly described in the survey. A more complete presentation of this question is given in [52].

Table 1
Basic Results of the Study of Radiowave Propagation in the Solar System

No.	Experiment	Spacecraft & Reference	Basic Result
1	Study of the atmosphere and ionosphere of Mars by radio occultation	Mars-2, Mariner-4, 6, 7 [1, 2, 8-11]	Dependence of pressure, temperature and electron concentration of the atmosphere and ionosphere of Mars on altitude was studied. Diameter of the planet was measured and its relief was studied.
2	Study of radiowave propagation in the dense atmosphere of Venus during descent of spacecraft to surface of planet	Venera-4, 5, 6, 7, 8 [12-18]	Direct experimental data were obtained on radiowave propagation through the entire atmosphere of Venus. Radiowave fluctuations were studied, which indicated turbulence of its atmosphere
3	Study of upper portion of atmosphere and ionosphere of Venus by radio occultation	Mariner-5 [23, 24]	Dependence of pressure and temperature in upper portion of atmosphere and electron concentration in ionosphere of Venus on altitude was determined.
4	Studies of reflection of radiowaves emitted by lunar satellites and of the lunar surface	Luna-11, 12, 14, 19, Explorer-35, Orbiter-1 [27-38]	Regularities of radiowave scattering by various portions of the lunar suface were studied. Dielectric constant of the soil and slope of surface heterogeneities were determined. A new method of study of the relief, dielectric constant and density of the planets and the moon was developed.
5	Study of propagation of monochromatic radiowaves in interplanetary and near-solar space	Mars-1, 2, Pioneer-6, Mariner-6, 7 [40-49]	Fluctuations, changes of spectrum and rotation of plane of polarization of radiowaves were studied. Parameters of electron concentration heterogeneity were determined. Distributions of electron concentration in near-solar and interplanetary space were measured. Measurement of the gravitational time lag of radiowaves in the field of grativity of the sun were carried out.

REFERENCES

1. Kolosov, M.A., O.I. Yakovelv et al, "Preliminary results of study of atmosphere of Mars by means of satellite Mars-2," Dokl. AN SSSR 206/5, 1071 (1972).

2. Kolosov, M.A., O.I. Yakovlev et al, "Radio occultation of atmosphere of Mars by means of spacecraft Mars-2," Radiotekhnika i elektronika 17/12, 2483 (1972).

3. Fjeldbo, G. and V.R. Eshleman, "The bistatic radar-occultation method for the study of planetary atmsopheres," J. Geophys. Res. 70/13, 3217 (1965).

4. Yakovleva, G.D. and O.I. Yakovlev, "Theory of radio occultation of the atmsophere of Venus," Radiotekhnika i elektronika 16/5, 665 (1971).

5. Andrianov, V.A., "Asymptotic solution of the problem of diffraction on a globe in a heterogeneous medium," Ibid. 13/8, 1374 (1968).

6. Andrianov, V.A., "The effect of the atmosphere of a planet on Fresnel diffraction of ultrashort radiowaves," Ibid. 14/8, 1355 (1969).

7. Phinnely, R.A. and D.L. Anderson, "On the radio occultation method for studying planetary atmsopheres," J. Geophys. Res. 73/5, 1819 (1968).

8. Fjeldbo, G. and V.R. Eshleman, "The atmosphere of Mars analyzed by integral inversion of the Mariner-4 occultation data," Planet. and Space Sci. 16/8, 1035 (1968).

9. Fjeldbo, G., A. Kliore and B. Seidel, "The Mariner 1969 occultation measurements of the upper atmosphere of Mars," Radio Sci. 5/2, 381 (1970).

10. Kliore, A., G. Fjeldbo and B. Seidel, "First results of Mariner-6 radio occultation measurement of the lower atmosphere of Mars," Ibid. 5/2, 373 (1970).

11. Kliore, A.I., D.L. Gain et al, "The atmosphere of Mars from Mariner-9 radio occultation measurements," Icarus 17/2, 484 (1972).

12. Kolosov, M.A., O.I. Yakovlev and A.I. Yefimov, "Study of decimeter radiowave propagation in the atmosphere of Venus by means of the unmanned interplanetary station Venera-4," Dokl. AN SSSR 182/1, 93 (1968).

13. Yakovlev, O.I. and G.D. Yakovleva, "Propagation of ultra-short waves in the atmosphere of Venus," Radiotekhnika i elektronika 14/4, 579 (1969).

14. Yakovlev, O.I., "Analysis of radiowave propagation in the atmosphere of Venus," in the collection Fizika Luny i planet [Physics of the Moon and Planets], Nauka Press, 1972.

15. Kolosov, M.A., O.I. Yakovlev and A.I. Yefimov, "Propagation of radiowaves in the atmosphere of Venus, from the data of the Venera-4, Venera-5 and Venera-6 spacecraft," Radiotekhnika i elektronika 15/12, 2473 (1970).

16. Kolosov, M.A., O.I. Yakovlev et al, "Fluctuations of radio-waves and heterogeneity of the atmosphere of Venus, from data of the Venera-4, Venera-5 and Venera-6 descent vehicles," Kosmicheskiye issledovaniya 8/6, 882 (1970).

17. Yakovlev, O.I., A.I. Yefimov and T.S. Timofeyeva, "Characteristics of radiowave propagation in the atmosphere of Venus and the interplanetary plasma from data of Venera-7 spacecraft," Ibid. 9/5, 748 (1971).

18. Yakovlev, O.I., A.I. Yefimov and T.S. Timofeyeva, "Radio-wave energy flux during descent of Venera-7 and Venera-8 vehicles to the surface of the planet," Ibid. 12/1 (1974).

19. Ho, I.A. Kaufman and P. Thadeus, "Laboratory measurement of microwave absorption in models of the atmosphere of Venus," J. Geophys. Res. 71/21, 5091 (1966).

20. Muhleman, D.O., "Microwave opacity of the Venus atmosphere," The Astronomical J. 74/1, 57 (1969).

21. Ingalls, R.P. and I.V. Evans, "Scattering properties of Venus at 3.8 cm," Ibid. 74/2, 258 (1969).

22. Wolf, D.A., "Evidence for several microwave signal fading in the atmosphere of Venus due to turbulence," J. Geophys. Res. 75/7, 1202 (1970).

23. Fjeldbo, G. and V.R. Eshleman, "Atmosphere of Venus as studied with the Mariner-5 dual radio-frequency occultation experiment," Radio Sci. 4/10, 879 (1969).

24. Fjeldbo, G., K.I. Kliore and R. Eshleman, "The neutral atmosphere of Venus as studied with the Mariner-5 radio occultation experiments," The Astronomical J. 76/2, 123 (1971).

25. Kazantsev, A.N. and D.S. Lukin, "Absorption of radiowaves in the ionosphere of Venus," Kosmicheskiye issledovaniya 7/6, 900 (1969).

26. Lukin, D.S., Yu.G. Spiridonov and V.A. Shkol'nikov, "Refraction of radiowaves and field strength in the atmosphere of Venus," Ibid., p. 905.

27. Yakovlev, O.I. and A.I. Yefimov, "Study of reflection of meter radiowaves by the surface of the Moon," Dokl. AN SSSR 174/3, 583 (1967).

28. Yakovlev, O.I., A.I. Yefimov and S.S. Matyugov, "Scattering of meter radiowaves by the surface of the Moon," Kosmicheskiye issledovaniya 6/3, 432 (1968).

29. Yakovlev, O.I., "Study of the lunar surface by the scattering of radiowaves of satellites of the Moon," in the collection Fizika Luny i planet [Physics of the Moon and Planets], Nauka Press, 1972.

30. Pavel'yev, A.G., "Scattering of electromagnetic waves on a rough surface and frequency spectrum of the reflected signal, " Radiotekhnika i elektronika 14/11, 1923 (1969).

31. Matyugov, S.S. and O.I. Yakovlev, "Scattering of radiowaves emitted by lunar satellites and interplanetary stations by the surfaces of the Moon and planets," Ibid. 15/2 (1970).

32. Matyugov, S.S., O.I. Yakovlev and B.V. Gritsaychuk, "Energy spectrum of radiowaves emitted by satellites of the Moon and reflected from the lunar surface," Ibid. 16/9, 1545 (1971).

33. Yakovlev, O.I., S.S. Matyugov and K.M. Shvachkin, "Parameters of scattered radiowaves and the nature of the lunar surface from Luna-14 satellite data," Ibid. 15/7, 1339 (1970).

34. Kayevitser, V.I., S.S. Matyugov et al, "Energy spectra of decimeter radiowaves reflected by the lunar surface from Luna-19 satellite data," Ibid. 19/5 (1974).

35. Tyler, G.L., V.R. Eshleman et al, "Bistatic-radar-detection of Lunar scattering centers with Lunar Orbiter-1," Science 157/3785, 193 (1967).

36. Tyler, G.L., "Brewster angle of the Lunar crust," Nature 219, 1243 (1968).

37. Tyler, G.L., "Oblique-scattering radar reflectivity of the Lunar surface: preliminary results from Explorer-35," J. Geophys. Res. 73, 7609 (1968).

38. Tyler, G.L. and R.A. Simpson, "Bistatic radar measurements of topographic variations in lunar surface slopes with Explorer-35," Radio Sci. 5/2, 263 (1970).

39. Fjeldbo, G., A. Kliore and B. Seidel, "Bistatic radar measurements of the surface of Mars with Mariner 1969," Icarus 16/3, 502 (1972).

40. Kolosov, M.A., O.I. Yakovlev et al, "Propagation of meter radiowaves in interplanetary space," Radiotekhnika i elektronika 9/10, 1735 (1964).

41. Kolosov, M.A., O.I. Yakovlev and A.I. Yefimov, "Propagation of radiowaves in interplanetary and near-solar space," Issledovaniya kosmicheskogo prostranstva [Space Research], Nauka Press, 1965.

42. Yakovlev, O.I., A.I. Yefimov and K.M. Shvachkin, "Attenuation of radiowaves in interplanetary and near-solar space," Radiotekhnika i elektronika 11/4, 617 (1966).

43. Yakovlev, O.I. and A.I. Yefimov, "Fluctuation characteristics and spectra of radiowaves in the interplanetary medium," Ibid. 11/11, 2064 (1966).

44. Yefimov, A.I., "Effect of the sector structure of interplanetary space on ultrashortwave propagation," Ibid. 14/12, 2091 (1969).

45. Yefimov, A.I. and O.I. Yakovlev, "Propagation of monochromatic radiowaves in the interplanetary plasma," Ibid. 16/9, 1554 (1971).

46. Yakovlev, O.I., B.P Trusov et al, "Study of propagation of radiowaves in near-solar plasma by means of the Mars-2 spacecraft," Kosmicheskiye issledovaniya 12/3 (1974).

47. Goldstein, R., "Superior conjunction of Pioneer-6," Science 166, 598 (1969).

48. Stelzried, C.T., C.S. Levy et al, "The quasi-stationary coronal magnetic field and electron density as determined by a Faraday rotation experiment," Solar Physics 14/2, 440 (1970).

49. Anderson, I.D., P.B. Esposito et al, "Determination of astrono-dynamic constants and test of the general relativistic time delay with S-band range and Doppler data from Mariner-6 and -7," Space Research, Vol. 11, Berlin, 1971.

50. Bucklei, R., "Fluctuations in the interplanetary plasma," Planet. and Space Sci. 19/5, 421 (1971).

51. Counselman, C.C. and I.M. Rankin, "Density of the solar corona from occultation of N P0532," The Astrophysical J. 175/3, 843 (1972).

52. Yakovlev, O.I., Rasprostraneniye radiovoln v Solnechnoy sisteme [Radiowave Propagation in the Solar System], Sov. Radio Press, 1973.